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## 1 Summary

This grant supported experimental research into high-speed laminar-turbulent transition. While it began as a one-year effort extending our earlier work on elliptic cones, it became increasingly evident that the low quiet Reynolds number available in the Mach-4 quiet Ludwig tube was limiting the usefulness of the measurements. Although useful results for instability and transition were nevertheless obtained, the emphasis shifted toward development of a high Reynolds number Mach-6 quiet Ludwig tube. Instrumentation development also continued, in the form of a series of experiments carried out at low quiet Reynolds number in the existing Mach-4 Ludwig tube. Experiments with the laser perturber, glow perturber, hot wire, laser-differential interferometer, and hot films are summarized. These experiments were carried out on elliptic cones, round cones, and a scramjet-inlet model.

## 2 Introduction

This grant was originally for one year, for continuation of our Mach-4 research, as described in the title. The grant was extended to 3 years by PR FQ8671-9701402 dated 11 June 1997.

At that time, the work was broadened to include the development of a high Reynolds-number Mach-6 quiet tunnel, with a 9-inch prototype followed by a 24-inch full-scale tunnel. Substantial AFOSR fabrication funds were to begin in FY99; initial fabrication had already commenced using Boeing gift funds. Subsequent changes at AFOSR, including a change of program manager, reduced the scope to the fabrication of the 9-inch prototype only, with AFOSR fabrication funding provided under the FY98 DURIP program. An FY99 DURIP award was later made, to provide additional facility-fabrication funding.

The results of the work funded under this grant are summarized here; more detail is available in the referenced publications. The work was also supported under DURIP grants F49620-98-1-0284 and F49620-99-1-0278, a gift from the Boeing company, a gift in memory of K.H. Hobbie, and Purdue University funding, including a 2-year student fellowship from the Purdue Research Foundation. Dr Takeshi Ito's labor was supported by a postdoctoral fellowship from the Japanese government. Accomplishments and publications are listed with only a minimal effort at apportionment. The work continues under AFOSR Grant F49620-00-1-0016; further publications are expected.

### 3 Results

#### 3.1 Laser-Perturbation Experiments on Elliptic Cone at Mach 4

These experiments were completed by John Schmisser during FY97, for his Purdue PhD, under the AFRL Palace Knight program [14]. Refs. [12], [15], and [13] showed that we were able to generate repeatable localized perturbations in the Mach-4 freestream. While the fluctuation amplitude (roughly 50%) was larger than is desirable for receptivity experiments, the repeatability of 1-2% was excellent. The perturbation is roughly spherical, with a diameter of 4-5 mm. It should be possible to generate smaller fluctuations using either a more careful tuning of the laser power, or a laser with a shorter pulse.

The measurements of the perturbation development on the elliptic cone were less successful, since the perturbation was not observed to grow substantially. This limitation is probably due primarily to the low Reynolds numbers that we are able to obtain under quiet flow conditions in the Mach-4 facility. However, the characteristics of a supersonic boundary-layer fluctuation induced by a freestream disturbance were repeatably measured, for the first time. A wave travelling at Mach 7 was detected near the shock wave (Fig. 21 in [12]); this appears to be the first repeatable detection of an induced wave travelling along a bow shock.

The mean boundary-layer profile on the semi-minor axis of the elliptic cone was also measured. While the effort uncovered some difficulties with calibrating the hot wire in the Ludwig tube, the boundary-layer thicknesses should be accurate, since the hot-wire position was measured directly with a telemicroscope. Fig. 12 in Ref. [12] shows that the boundary layer computed by Huang and Herbert [2] is about 28% thinner than the measured layer. This points to the difficulty of computing these 3D supersonic boundary layers. The experimental thickness is now available to provide validation for future computations of this type.

### 3.2 Other Laser-Perturbation Experiments

The laser perturber was also used to investigate the flow on a forward-facing cavity [6]. Repeatable measurements were obtained, including the damping rate of the induced oscillations. The damped oscillations observed explain the low levels of cavity fluctuations observed under quiet flow conditions. These levels are more than an order of magnitude lower than those observed under noisy conditions in conventional tunnels. The difference provides an explanation for the low levels of heat transfer observed in two flight tests carried out ca. 1960. These flight heat-transfer levels were an order of magnitude lower than any that have been observed in conventional ground tests. The combination of the laser perturber and the quiet tunnel has finally a convincing explanation for this flight anomaly.

The laser perturber is also being used in the blunt-body receptivity measurements of Salyer [11, 10].

### 3.3 Measurements of Turbulent Spots Using Hot-Film Arrays

The second goal of the original research plan was to generate turbulent spots using a glow perturber, and observe their growth along the surface of the elliptic cone, using the surface hot film arrays. Ten constant-temperature anemometers were built to perform these measurements, at a cost of about \$500 per channel, an order of magnitude less than the cost of commercial anemometers. While the bandwidth of these anemometers is only about 10-20 kHz when connected to the hot-film sensors, this bandwidth is well suited to the limited-bandwidth surface films, and the noise level is substantially lower than that of our TSI IFA-100.

While these anemometers have been successfully used to detect transitional intermittency [3, 13], it turns out that the bandwidth is insufficient to reliably characterize the convective velocity of turbulent spots [8, Section 2.3]. Successive streamwise sensors are readily able to detect the telegraph-like signal characteristic of a succession of turbulent spots. In addition, a consistent pattern of long and short duration spots can be observed on successive sensors without difficulty. However, the relative timing of the spot arrival cannot be determined with sufficient accuracy, even after attempts to calibrate the impulse-delay of the anemometers using a square wave that is simultaneously applied to all. The spot-passage time of roughly 0.01-0.1 ms is just too fast for the hot-film frequency response.

Use of the hot films for detection of turbulent spots and transition intermittency was nevertheless very successful. The effect of surface roughness and tunnel noise on scramjet-inlet intermittency was successfully measured [3]. The spanwise uniformity of the laser perturbation on the elliptic cone was also detected using these sensors [13], as was the spanwise uniformity of intermittency onset due to increases in tunnel operating pressure.

### 3.4 Glow-Perturber Measurements of Controlled Wave Growth

When it became evident that controlled study of turbulent spot growth was going to be very difficult with the present instrumentation, the development of the glow perturber was instead focused on controlled measurements of instability-wave growth. Although these

measurements were originally to be carried out on the elliptic-cone model, difficulties with development of the glow-discharge apparatus delayed this work. While it is not hard to produce a discharge on an electrode, it proved difficult to generate a repeatable high-frequency glow discharge with sufficiently low levels of radiated electromagnetic interference (EMI). A number of glow-discharge electrodes were developed and tested. Due to the risk and expense of installing these in the complex elliptic-cone model, initial experiments were carried out on a low-cost sharp round cone.

Although the EMI problem remains to be resolved, sufficient progress was made to allow making repeatable measurements using packets of instability waves. The hot-wire measurements are carried out after the glow discharge is turned off, and the resulting perturbations are allowed to convect downstream. Repeatable wave growth of a factor of 2-3 was observed on the round cone at angle of attack [5, 4]. The repeatability of the RMS amplitude was 4.5%. The eigenfunction of the fluctuation profile in the wall-normal direction was also determined, along with a roughly-calibrated mean-flow profile. Unfortunately, the wave growth observed was far less than the factor of roughly 4000 that normally leads to transition under low-noise condition. The limited wave growth that could be observed is due to the limited, low Reynolds numbers that it is possible to achieve under quiet-flow conditions in the Mach-4 facility. The glow electronics were successfully operated to 1 MHz, suggesting that high-frequency second-mode waves could be generated under the right flow conditions [4].

### 3.5 Laser-Differential Interferometer (LDI) Development

The first two years of the present grant continued funding for development of this apparatus, which is the only known optical method capable of detecting low-amplitude high-frequency instability waves under low-density hypersonic conditions [1]. The optical pathlength sensitivity limit has been reduced to  $1/15,000$  of a wavelength [11, 10], which is far better than imaging methods, and within a factor 6 of the  $1/100,000$  achieved by Smeets [27]. A number of critical German reports were obtained from Smeets, translated, and checked by him before his retirement. These English translations have been archived by DTIC [29, 26, 28, 25].

Ref. [10] reports repeatable measurements of the oscillations of the subsonic region of a blunt hemisphere at Mach 4; the oscillations are induced with a laser perturbation that impinges from the freestream. A forthcoming PhD thesis should provide validation-quality results for computations of this complex unsteady flow, which is closely related to hypersonic blunt-body receptivity. This flow was selected in place of the elliptic-cone receptivity to the laser perturbation, since the elliptic-cone flow has such small fluctuation growth. It should be emphasized that these results were obtained in an actual operating Ludwig tube, so that many facility-related optical difficulties were overcome. These include noise and facility vibration. Successful use of the LDI in the blunt-body problem will be an important milestone toward later use for study of second-mode waves.

### **3.6 Development of the 9.5-inch Mach-6 High Reynolds Number Quiet Ludwig Tube**

Work on this project commenced with an AFOSR proposal submitted in Feb. 1996 [24]. This work built on Prof. Schneider's work for NASA Langley, beginning in 1990, and on Langley work beginning from the late 1960's. The aerodynamic design of the Mach-6 quiet nozzle was reported in Jan. 1998 [19]. The detailed mechanical design was reported in June 1998, along with the aerodynamic design of the contraction [18]. A summary of the project was reported at the IUTAM meeting in Sept. 1999 [22]. The present state of design, fabrication, and testing was recently reported in Jan. 2000 [23]. Some additional detail will be reported, along with restricted-access cost information, in the final report for the FY98 DURIP grant (F49620-98-1-0284). Completion is currently scheduled for Fall 2000.

### **3.7 Transition Surveys**

A review of the flight-test data for hypersonic and supersonic transition was developed and published [20, 21]. This was thought to be particularly important in view of the great expense involved in obtaining this data, the number of little-known publications involved, and the fact that most of the workers familiar with this literature have retired or are near retirement. A review of the effect of tunnel noise on the trends in high-speed transition was also prepared and published [9]. An updated version of this work is to be presented as an invited paper during the June 2000 AIAA meeting.

### **3.8 Ongoing Efforts**

Work continues on the Mach-6 quiet tunnel. Two major experiments in this facility are currently funded: the scramjet forebody for AFOSR, and a small-bluntness round cone for Sandia.

In addition to these funded efforts, measurements are to be made using the glow perturber on the elliptic cone at angle of attack, by Laura Randall. This work would be carried out for a forthcoming PhD thesis, in the Mach-4 facility.

All of these measurements require the use of a calibrated hot wire. Since the previous hot-wire calibrations in the Mach-4 Ludwig tube may have suffered from slow unsteady heat-transfer to the prongs, our 1-inch undergraduate supersonic jet facility was modified to form a Mach-4 or Mach-6 calibration jet for the hot wire [16, 17]. The facility uses the filters and heaters originally installed to heat the Mach-4 Ludwig tube [7]. This work was carried out by an undergraduate, Phil Schneider, funded in part under a Bruhn summer fellowship from Purdue. This calibration work is being carried on by Laura Randall and Shann Rufer. Ms. Rufer's work is presently funded through the Sandia project.

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